Polarized ^{3}He Source Development at MIT

- Development of a design concept to produce polarized $^3He^{++}$ using existing EBIS
- In the process of putting together a laboratory on the MIT campus to support the realization of this source

Charles Epstein and Richard Milner

Work supported by:

- The DOE Office of Nuclear Physics, R&D Program for Next Generation Nuclear Physics Accelerator Facilities
- MIT Department of Physics

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Motivation

- Polarized ^{3}He is an effective polarized neutron: magnetic moment approximates that of free neutron so existing spin manipulation in RHIC, which was designed for protons, will also work for polarized ^{3}He

- With polarized ^{3}He beams in RHIC, new, high-energy QCD studies via polarized neutron collisions become possible

- Tests of the standard model in a new electron-ion collider eRHIC become possible

History

- 8 particle μA, 10% polarization - $^3He^+$
  - Rice University, 1969 (Metastability exchange optical pumping)
- 50 particle nA, 65% polarization - $^3He^+$
  - University of Birmingham, UK, 1973 (Lamb-shift)
- 100 particle nA, 95% polarization - $^3He^+$
  - Laval University, Canada, 1980 (Stern Gerlach method)

Another Approach

- 8μA, 10% polarization
- Singly charged
- Rice Univ., 1969

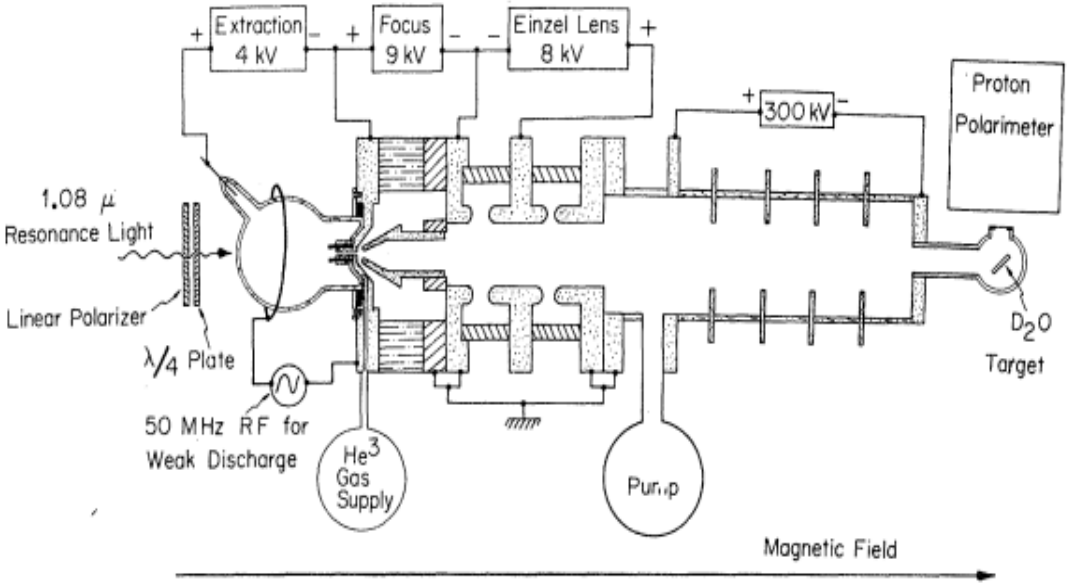
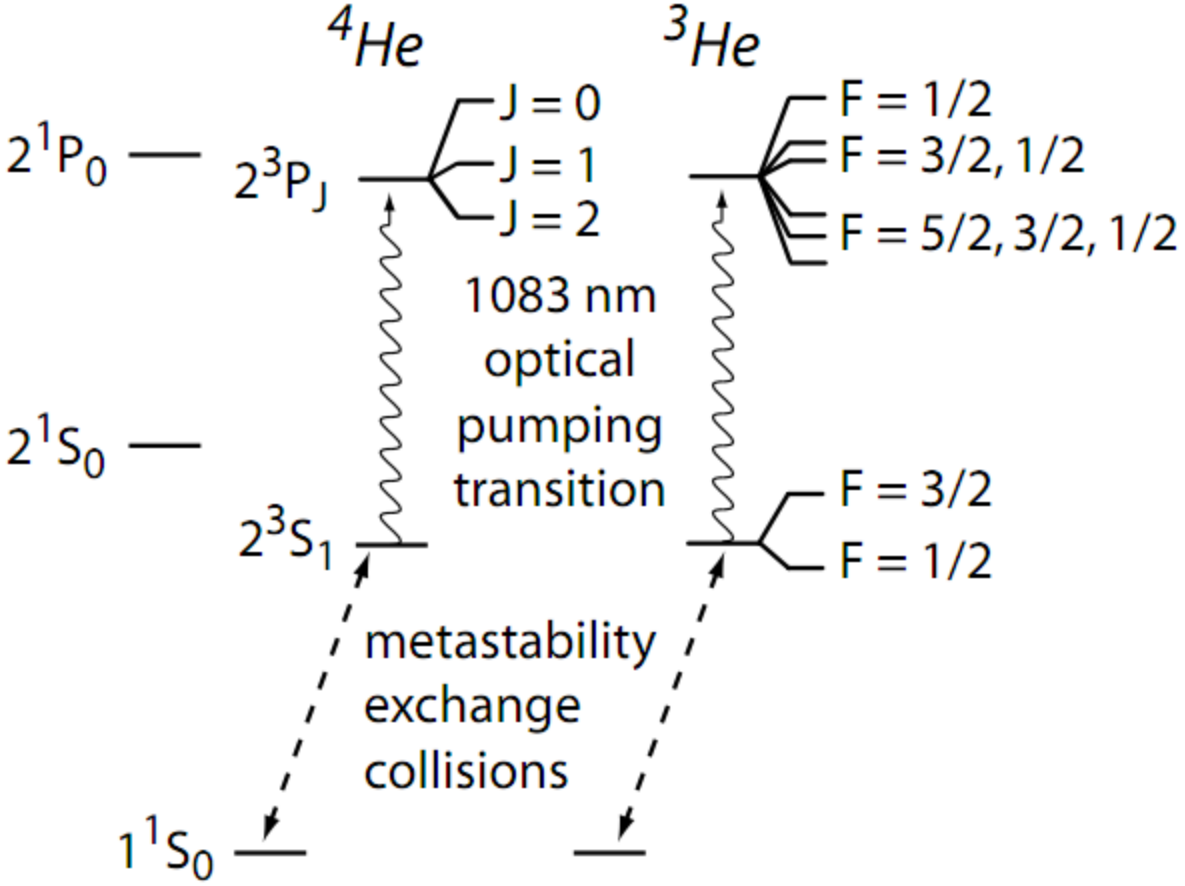


FIG. 1. Schematic view of apparatus used to produce a beam of polarized He^3 ions and to measure their polarization. A description of this figure is given in the text. The part of the drawing showing the optical pumping cell, the gap lens, and the einzel lens is approximately to scale.

Goal

- ≈ 3×10^{12} /sec (500 particle nA), 70% polarized $^{3}He^{++}$ into RHIC
- To produce a polarized $^{3}He^{++}$ source using the existing Electron Beam Ionization Source (EBIS) at BNL
- Requires a source of polarized ^{3}He atoms which are directed into the EBIS
- Pulsed structure: ≈ 1 second pulse, ≈ 3 seconds off

Metastability Exchange Optical Pumping



Colegrove, Schearer, and Walters 1963

Mature technology

- Can deliver highly polarized (≈ 90%), pure samples of ≈ 10^{18} atoms of ^{3}He gas in ≈ 10 seconds.
- Commercially available, powerful lasers at 1.083 μm
- Nuclear and particle physics targets developed (Caltech, MIT, Mainz) and successfully utilized (MIT-Bates, NIKHEF/AmPS, DESY/HERMES, Mainz)
- Used in medical imaging (Mainz) and as a neutron polarizer (ILL)

MEOP at High Magnetic Field

- Developed in the last decade for medical applications

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High nuclear polarization of ^{3}He at low and high pressure by metastability exchange optical pumping at 1.5 tesla

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MEOP at High Magnetic Field

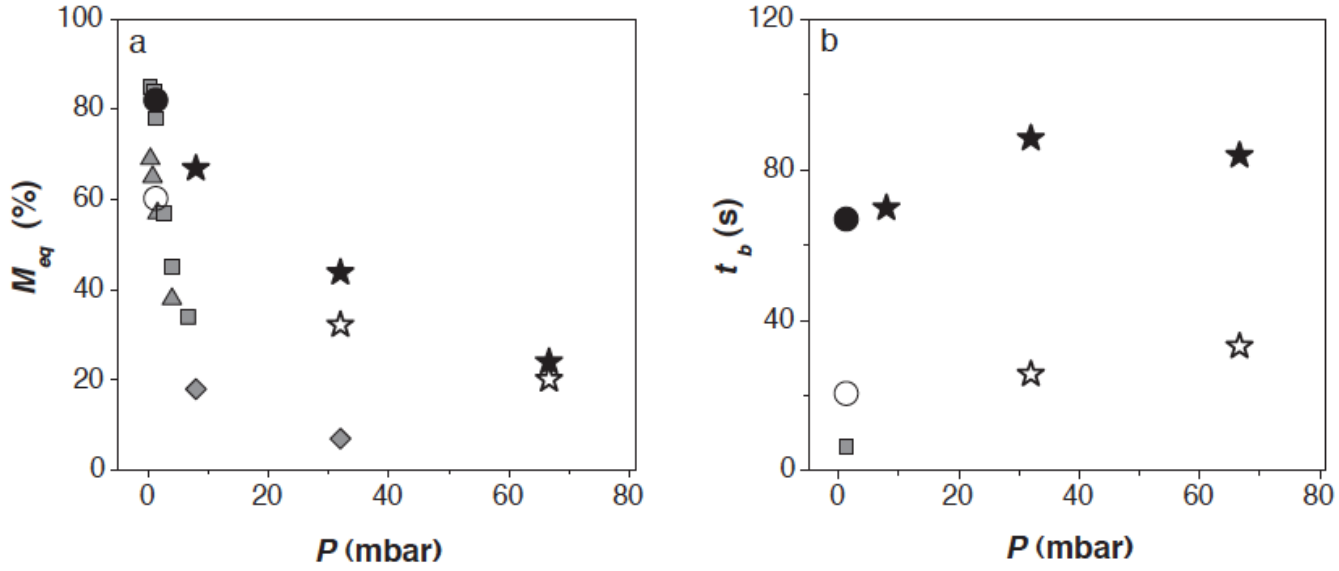


Fig. 5 – (a) Steady-state polarization, and (b) polarization build-up time constant, as a function of ^{3}He pressure P, at high and low magnetic fields. Circles and stars are 1.5 T data obtained with a broad-band (2 W) and single-mode (0.5 W) pump lasers, respectively. Filled (open) symbols are for weak (strong) discharge: T_1 = 300 (60), 2600, 1600 (325), and 1300 (700) s for 1.33, 8, 32, and 67 mbar, respectively. Triangles, squares, and diamonds are low-field data published in [5,6], and [7], respectively (all for weak discharges).

Electron Beam Ionization Source

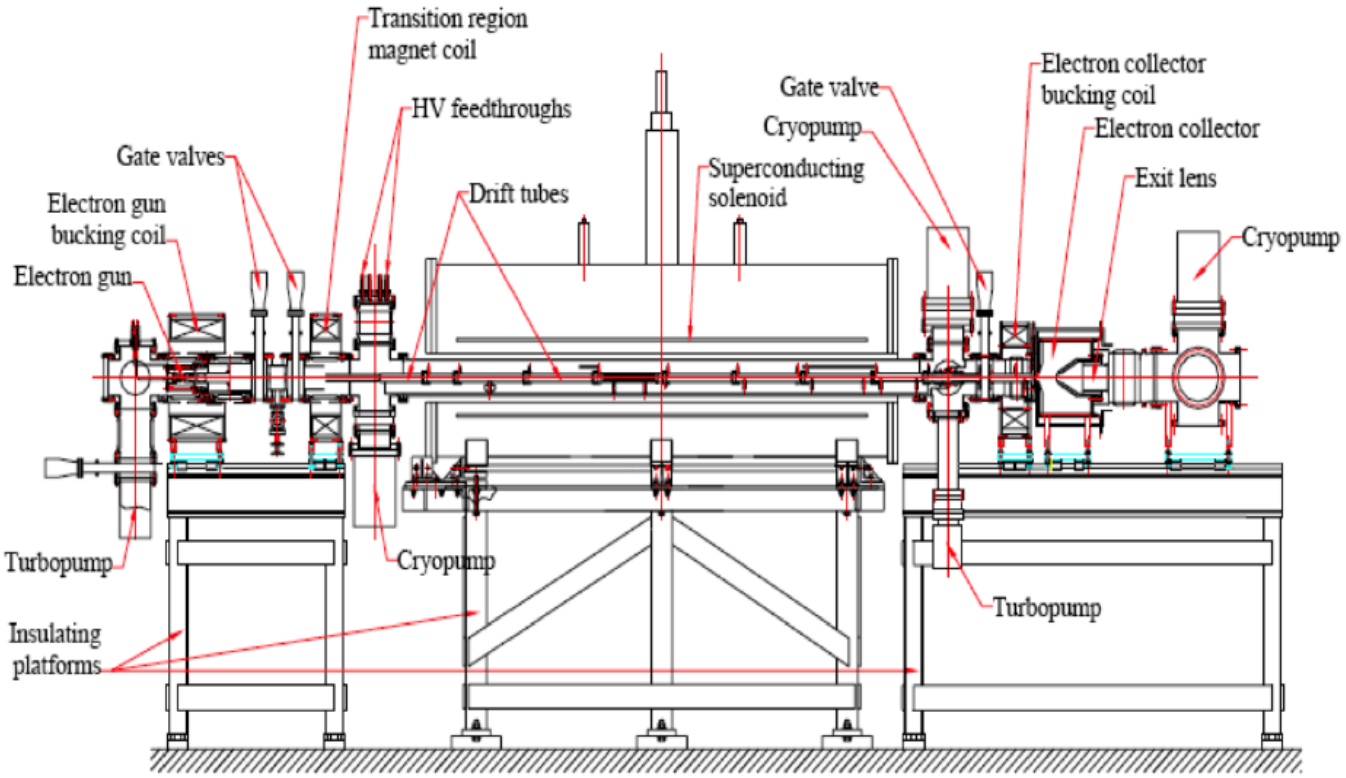


FIGURE 3. A detailed schematic of EBIS

- 5T Solenoidal field
- 1.5 m ion trap
- 10A of 20 keV electrons
- 575 A/cm^2 current density

Electron Beam Ionization Source

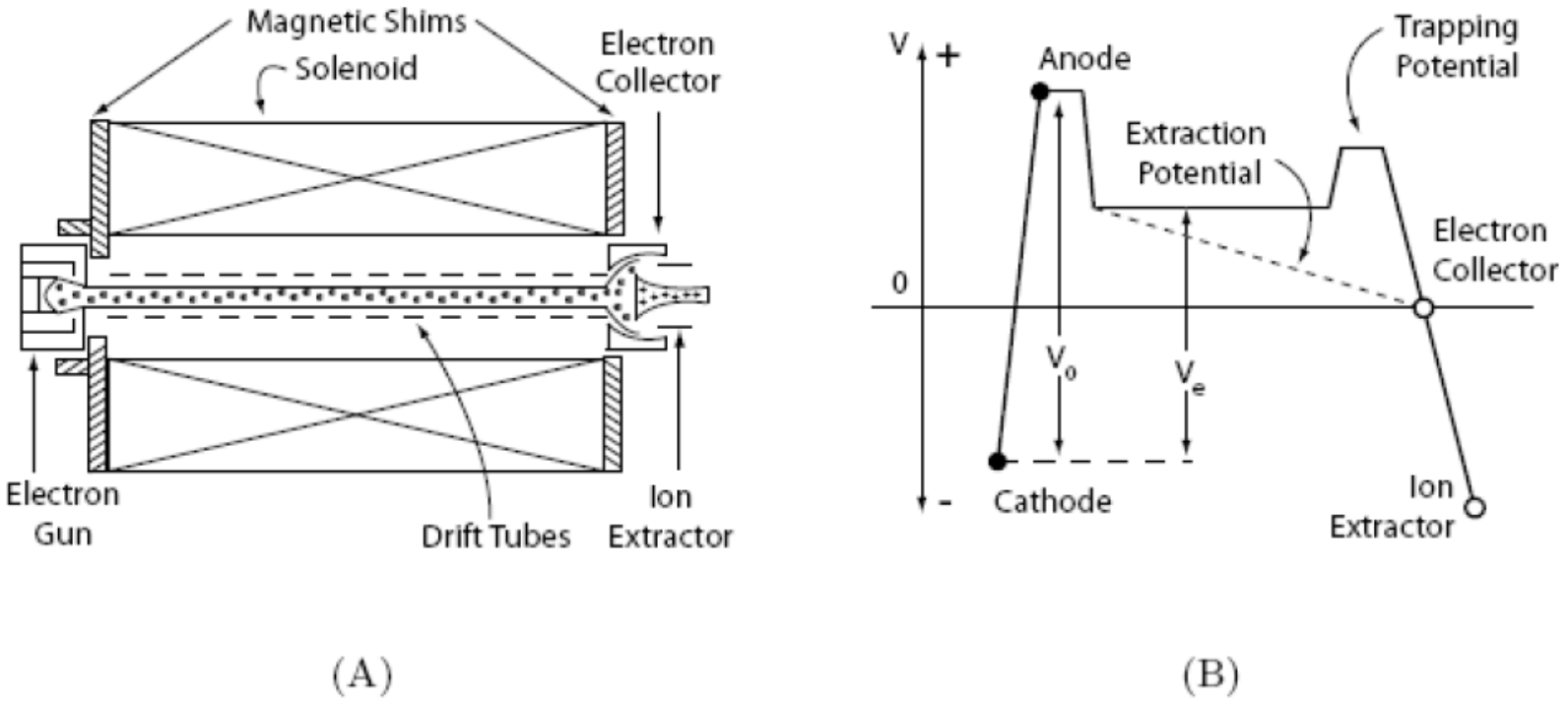


Figure 4. (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.

Choice of location of pumping cell

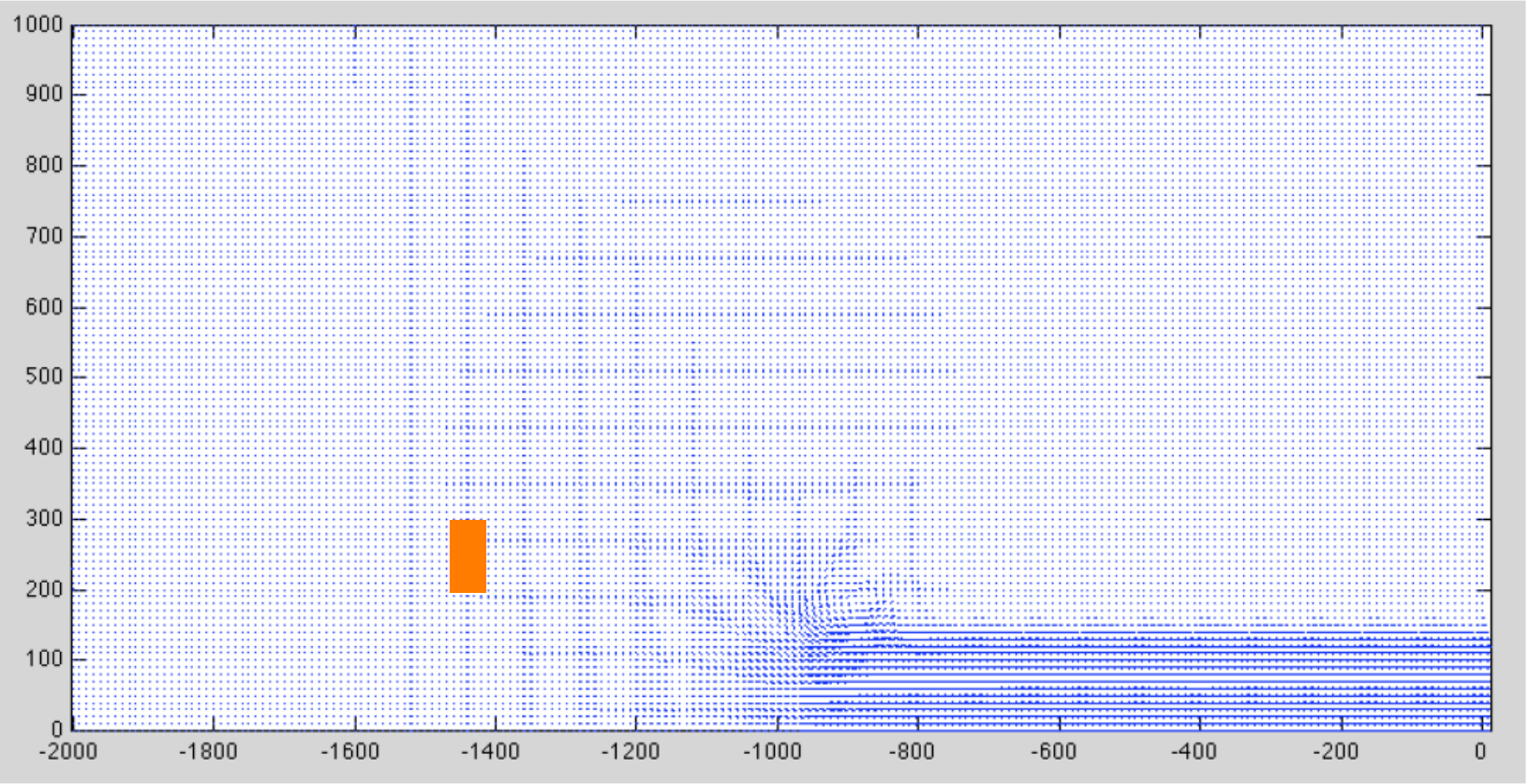


Figure 1: The field on the gun side. Units are in mm.

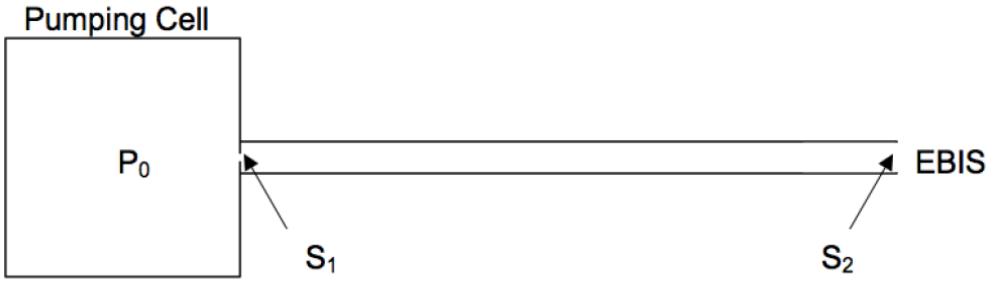


FIGURE 4. Schematic layout showing definition of variables

Concept

- Locate ^{3}He gas in a glass pumping cell in the fringe field of the EBIS solenoid (field ~ 0.1 Tesla)
- Polarize gas at ~ 1 torr pressure in pumping cell using metastability exchange optical pumping
- Measure polarization in pumping cell using pump-probe technique
- Feed polarized atoms via calibrated leak in pumping cell along tube into EBIS
- Plan to test concept by collecting sample of atoms at end of beam tube and measuring their polarization using NMR

Details

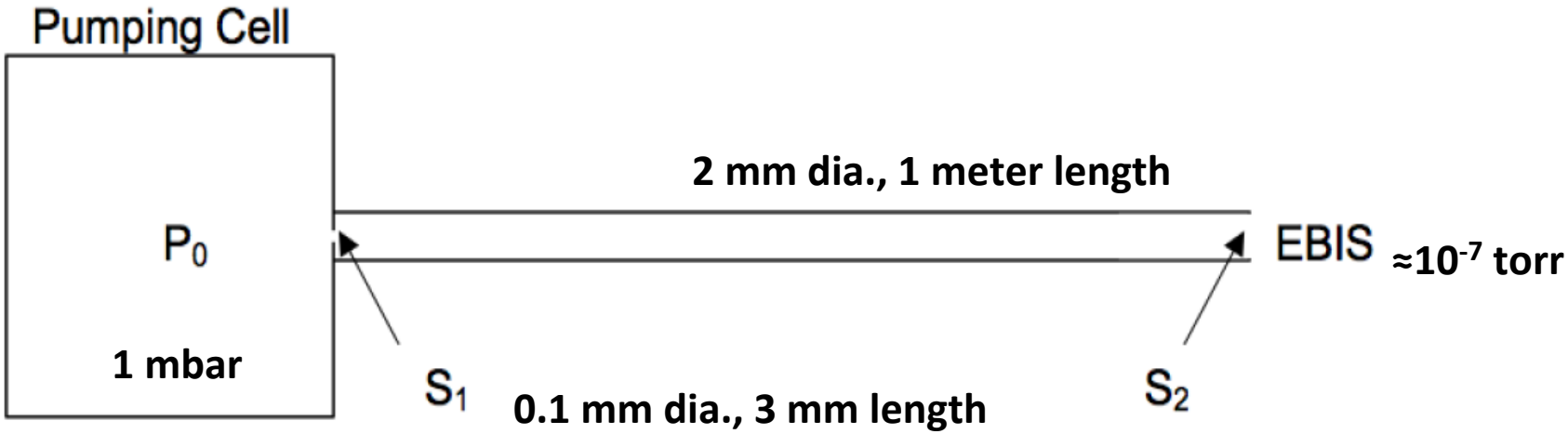
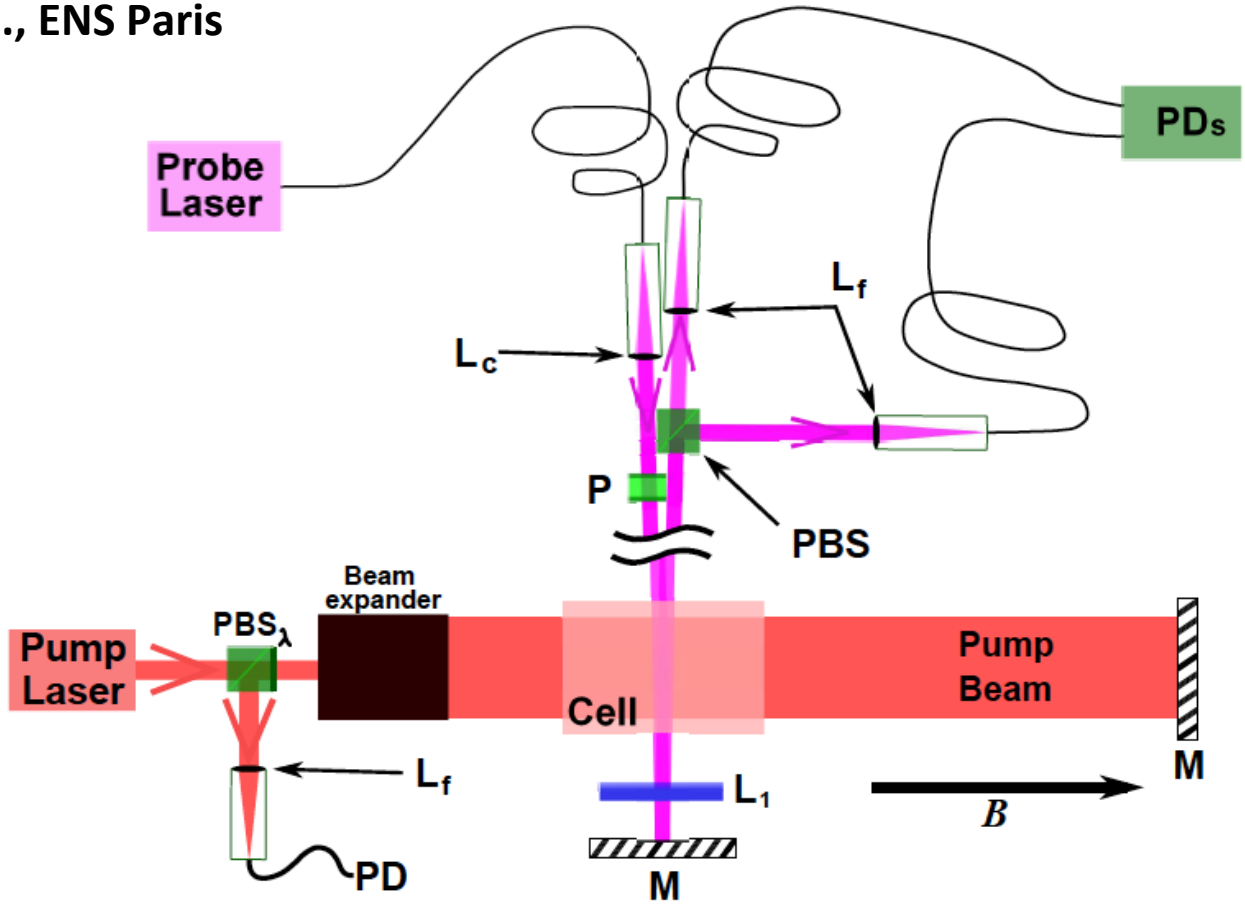


FIGURE 4. Schematic layout showing definition of variables

- ≈ 10^6 bounces in 1 meter long transfer tube
- Negligible wall depolarization
- Transfer time ≈ 1 msec
- Configure test where polarized atoms are contained in storage cell at the end of the transfer line – can measure the loss of polarization using NMR

^{3}He Polarization Measurement in Pumping Cell

C. Talbot et al., ENS Paris



NMR calibration of optical measurement of nuclear polarization in ^{3}He

W. Lorenzon, T. R. Gentile, H. Gao, and R. D. McKeown
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 June 1992)

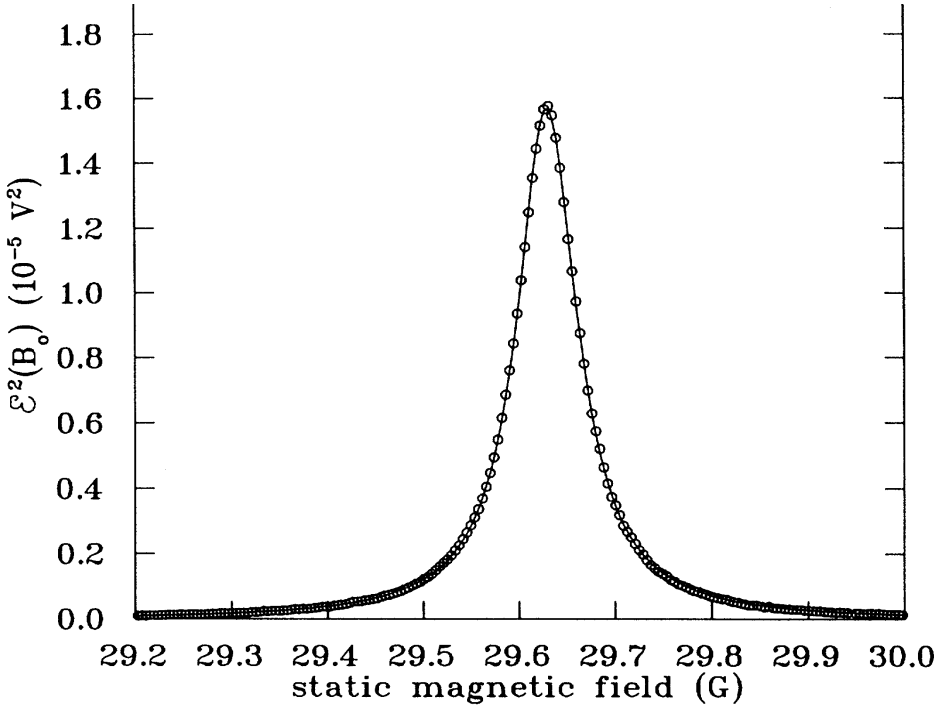


FIG. 6. Adiabatic fast-passage signal for a 1.0-torr cell of ^{3}He ($P_n = 64\%$). The solid curve is a fit to a Lorentzian distribution.

Depolarization

- Wall bounces
- Magnetic field gradients

$$\frac{1}{\tau} = \frac{2}{3}\frac{|\Delta B_t|^2}{|B_l|^2}\langle v^2\rangle \frac{\tau_c}{\omega_0^2\tau_c^2+1}$$

- τ = polarization relaxation time
- ΔB_t = transverse gradient in Gauss/cm
- B_l = holding field in Gauss
- $\langle v^2\rangle$ = mean-squared velocity in cm/s
- $\omega_0 = 3.24|B_l|\ kHz$ with B_l in Gauss
- τ_c = average time between collisions (sec)
  $\approx 2.2 \times 10^{-7} p^{-1}$

Magnetic Field Gradients

- ≈ 0.1T Field outside EBIS (solenoid fringe)
- Contains strong gradients, depolarization in ≈ 1 second
- Cancellation coil is necessary to prevent quick depolarization

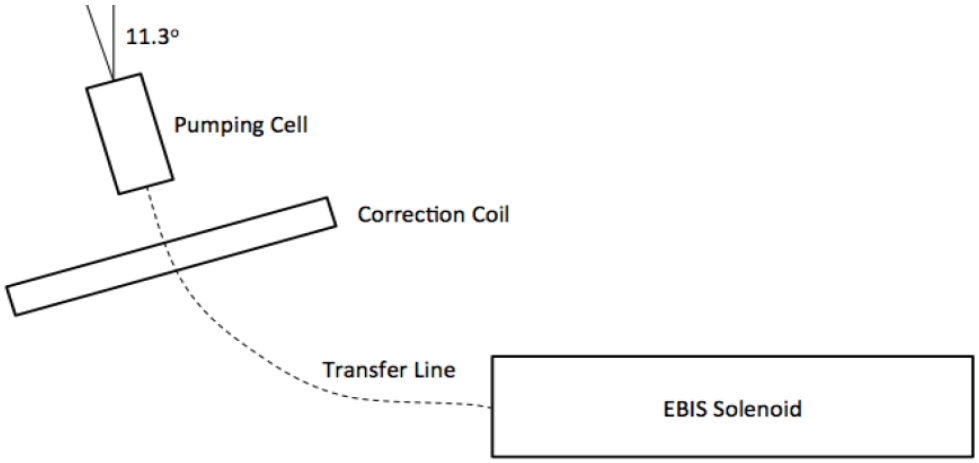
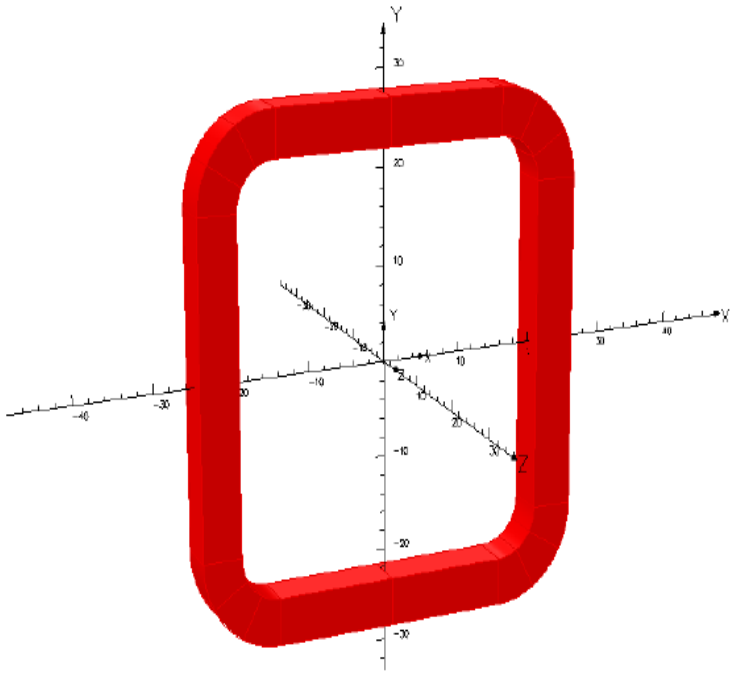


FIGURE 5. Setup schematic (not to scale)

Coil properties

- 6,000 A, 25 cm^2 (air cooled)
- 45 cm x 50 cm, rectangular
- Relaxation times ~600 seconds (more than sufficient)



Reversing the Polarization

- Simultaneously reverse the circular polarization of the pumping light and reverse the polarization of the atoms in the pumping cell via *adiabatic fast passage* NMR in ≈ 1 sec

$$\mathbf{B}_e = \left[B_0 - \frac{\omega}{\gamma} \right] \mathbf{k}' + B_1 \mathbf{i}'$$

adiabatic

$$\left| \frac{dB_0}{dt} \right| << \gamma B_1^2$$

$$\frac{\gamma}{2\pi} = 3.24 \text{ kHz/G}$$

fast

$$\frac{1}{B_1} \left| \frac{dB_0}{dt} \right| >> \frac{1}{T_1}, \frac{1}{T_2}$$

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Powerful and compact sources are desirable for massive production of ^{3}He gas.
A new generation of fiber lasers is now available. The master oscillator power amplifier design relies on the use of a seed fiber laser which has adjusted linewidth of 1.8GHz to achieve optimum pumping of ^{3}He and ^{4}He atomic transitions.

Atomic Processes in EBIS

- **Ionization** in EBIS: 10^{10} MeV/sec deposited by the electron beam
  100x the power needed to fully ionize all extracted ions
  ^{3}He will be fully ionized in EBIS to $^3He^{++}$
- What processes inside EBIS can cause depolarization?
- **Charge exchange**: $^3He^+ + {}^3He^{++} \rightarrow {}^3He^{++} + {}^3He^+$
  - $\sigma \approx 10^{-16}$ cm^2, approximate rate 10^7 s^{-1}
- **Recombination**: $e^- + {}^3He^{++} \rightarrow {}^3He^+$, which can depolarize
  - Radiative 3-body process: unlikely
  - Factor of $1/\alpha^2$, $\sigma \leq 10^{-20}$ cm^2
- **Spin-exchange collisions**:
  - For H, $\sigma = 10^{-14}$ cm^2; He^{++}/He^+ should be much lower
- Are there other processes?

Major tasks ahead

- Polarize sealed cells: V≈100cm^3 to P≈80%
- Develop feed system with a calibrated leak
- Develop pump-probe measurement of polarization
- Construct test at BNL using EBIS solenoid
- Measure polarization of sample of atoms using NMR

Summary

- Concept developed to deliver polarized ^{3}He atoms to the existing EBIS with high polarization at the required flow rate
- With careful location and configuration of the polarized atom source depolarization effects estimated to be small
- Source construction getting underway with goal to carry out test on EBIS solenoid
- Post-doctoral research support critical to make progress in a timely way.